A STUDY OF LIMINAL SOUND INTENSITIES AND THE APPLICATION OF WEBER'S LAW TO TONES OF DIFFERENT PITCH

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That the normal human ear is not uniformly sensitive to all gradations in the tonal scale has become a recognized physical fact. The absolute limit of that sensitivity, however, and a measure of the absolute intensity required to elicit response to different pitches are factors which, so far, have never been wholly determined. Very slow and very fast vibrations we either do not hear or else hear uncertainly; and the character of these turning points, *i.e.*, whether they are sudden disappearances or gradual declines, as well as the possibility of varied sensitivity to pitches within these boundaries, have proved an interesting problem both from a physical and a psychological point of view.

In reviewing the literature on auditory phenomena, we find that the bulk of sound experiments comprises such phases as pitch discrimination, the much mooted question of tonal attributes, and physiological theories, with a very meagre contribution in the nature of quantitative measurements of intensity or the audible limits. The material in the following table (A), taken with permission of Professor Pillsbury from the *Psych. Review Mon. Supp.*, 13, 1911, and supplemented with an addition from Gildemeister, summarizes practically the whole of the available quantitative data.

Many of the earlier psychological investigations of sound were carried on with freely falling balls and pendulums; but these apparatus tended rather toward controversy over physical formulae than toward adequate conclusions. For his measurements of sound intensity, Lord Rayleigh used metal cans with vibrations induced through an electromagnet. His results are larger than Wien's, and are limited to determinations of just two pitches in the lower middle range. Toeppler and Boltzmann utilized closed tubes, in which the concentration of sound was measured by a method of interference.

Tuning forks, both electrically and simply driven, have furnished a considerable bulk of experimental data. They were employed in the investigations of Zwaardemaker and Quix, Wead, Stumpf, and by some of the more recent experimenters, all of whose results nevertheless refuse to harmonize on the ground of a common apparatus. This disparity may be due to

TABLE A

N	*WN.*	*R.*	*ZW.& Q*	*WD.*	*T.&B.*	*G.*
32						Upper limit (15000–20000 vd.)
50	4.10^{-6}					0.2–0.5 watt
64						
96			$2,8.10^{-1}$			
100	7.10^{-9}					
128			$2,7.10^{-1}$			
181					3.10^{-6}	
192			$4,6.10^{-1}$			
200	3.10^{-11}					
256		$8,5.10^{-9}$	$5,5.10^{-2}$	83.10^{-6}		
384		6.10^{-9}	$3,4.10^{-2}$	28.10^{-7}		
400	3.10_{-14}					
512			$1,97.10^{-3}$			
768			$2,5.10^{-4}$	31.10^{-7}		
800	7.10^{-15}					
1024			$2,7.10^{-4}$	11.10^{-7}		
1536				22.10^{-6}		
1600	1.10^{-15}					
2048				71.10^{-7}		
3200	5.10^{-16}					
6400	3.10^{-15}					
12800	5.10^{-14}					

The values in the first column represent the rate of vibration of the various tones. The succeeding columns include the energy in ergs required for minimal intensities of these tones as determined respectively by Wien, Rayleigh, Zwaardemaker and Quix, Wead,[1] Toeppler and Boltzmann, and Gildemeister.

[1]Wead's measurements represent the energy in the tuning fork itself. The energy affecting the ear would be much less.

the difficulties inherent in the tuning forks themselves, or perhaps to differences in the psychophysical methods of acquiring results.

A recent experiment dealing primarily with the upper audible limit, but affording also its quantitative equivalent in energy, is that of Gildemeister. His apparatus utilizes a condenser and induction coils, and has many factors in common with the apparatus we employ in our work at Michigan.

Weiss has also investigated the sound-intensity reaction, using electrically driven forks and shifting resonators. His aim is not so much to determine actual limens as to secure evidence for his physiological theory; but some of his results correlate with pertinent phases of Weber's law. He found that when the resonators are near the fork the just-noticeable differences are shorter steps than when the resonators are farther away, and that this increase in length is approximately a logarithmic series. Weiss found also a rather marked disparity between individual discriminations within the same "critical range."

In reviewing apparatus, a mention of the transmitter of Wente and the thermophone of Arnold and Crandall should not be omitted, although pertinent results from their work are not yet available.

It is Wien's determinations of liminal sensitivity, however, which are of the most relevant interest here. His work, in fact, affords probably the most authoritative, and certainly the most comprehensive reference for tones of weak audibility; and his apparatus, based on the theory that the energy of the increasing stimulus serves directly as a measure of the mass of the sensation, has provided a workable model for use in our own telephone set-up. He has left results, however, only for tones ranging from 50 vd. to 13,000 vd., and the validity of these is somewhat lessened by the fact that he apparently used only himself as subject, thus omitting the factor of individual differences in auditory acuity.

As the manuscript is finished the articles of Bunch and Zuehl appear in the University of Iowa studies. They used a method of inducing the pitch by varying the rate of rotation of an armature near electromagnets. The results are given only relatively in terms of the resistance required to reduce to zero the tone produced by a standard current. This procedure neglects the fact that the intensity of the sound varies as the square of the rate of vibration as well as with the amplitude. The rapid falling-off in sensitivity above 750 vd., which Zuehl's curves show as compared with our measurements and Wien's, is to be explained by this fact.

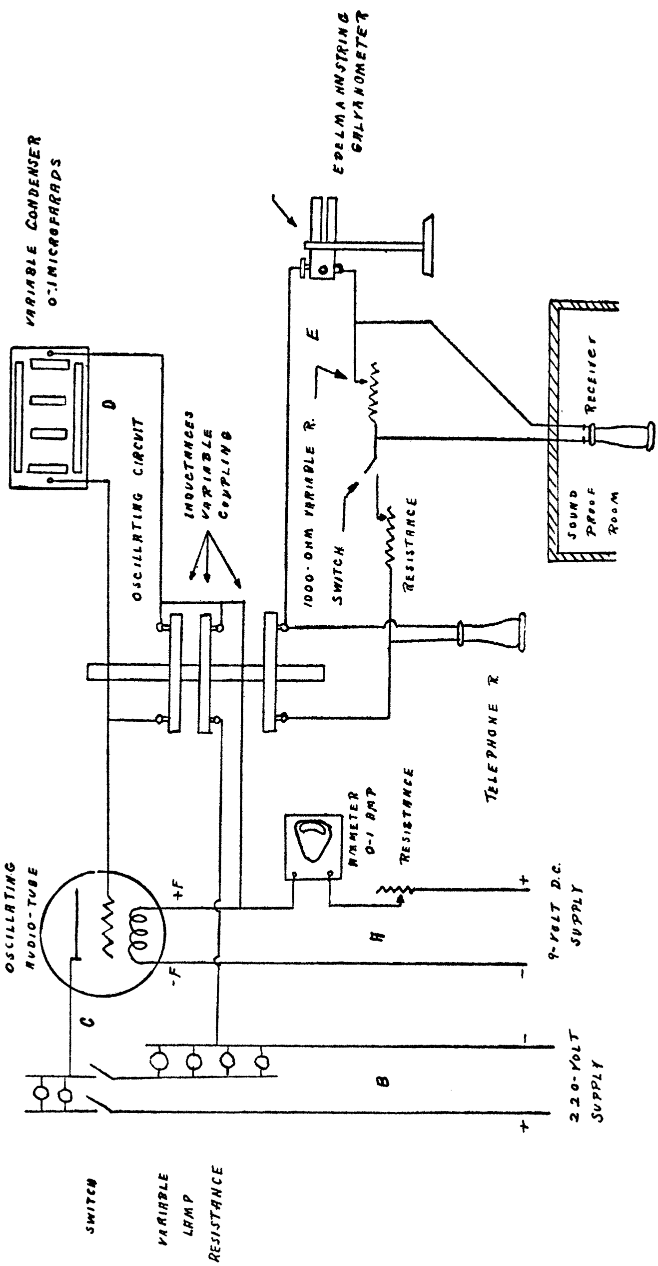
The Helmholtz resonance theory favors a hypothesis of sudden turning points of intensity in the tonal scale. Wien has challenged this assumption by a series of experiments which, though maintaining definite turning points, makes them rather gradual, and recurring through several octaves. In general, Wien found that the curve of liminal intensity in hearing increases markedly from the lowest audible tones to those of 3,000 vd., where it begins to diminish, at first slowly, then more rapidly. The region between 1000 and 5000 vd. elicits the greatest sensitivity. These latter results are apparently substantiated by the work of Gildemeister, though only one definite measurement is offered in his article.

From the foregoing brief review, it will be seen that the apparatus hitherto used for determining sound intensity roughly classifies into five main divisions: (1) use of pendulums, falling balls, etc.; (2) use of discs and resonators; (3) use of tuning forks and electromagnets; (4) use of direct optical methods for observing the motions of a vibrating diaphragm; and (5) use of telephone transmitters with subsidiary apparatus. Our apparatus in the laboratory at Michigan uses a combination of the last two.

All of the methods, of course, presuppose the same physical and physiological factors of sound phenomena: namely, that the intensity of the sensation depends in rough measure upon the kinetic energy of the vibrating medium, and that at the same time the ear, in reporting it, is affected by subjective conditions of perception. The same intensity, for instance, will appear to be different for different *O*s, and even for the same *O*s on different days or under different experimental conditions, and this factor has added decidedly to the complexity of establishing rigid measures of absolute intensity. Our experiment has consequently been conducted on a quantitative basis, and has consisted of taking a large number of measurements of minimal intensities at different vibration rates, using trained *O*s under controlled conditions.

Apparatus

Our apparatus utilizes vacuum-tube oscillation, thus providing a novel method of obtaining pitch differences by electrical tuning such as that used for high frequency amplification in wireless communication. The principal factors in the tuning circuit are a vacuum tube, coils for self-induction, and a condenser of variable capacity for changing the pitch. To the induction circuit is also attached a galvanometer which provides a direct means of measuring the amplitude of oscillation of the current. Two current sources are employed, one from a battery of sufficient voltage (9–12 volts) to heat the filament of the tube,



APPARATUS PRODUCING LIMINAL INTENSITIES.

the other from a power source of 220 volts d.c. The grid is in series with one coil and the condenser; the plate, with a second coil. We thus have two currents which, through mutual induction, start each other into oscillations at a rate determined by the amount of self-induction and capacity in the circuit.

The telephone circuit is composed of a third coil, the telephone receiver, a known variable resistance, and an Edelmann string galvanometer. The last instrument is substituted for the dynamometer of Wien, with the probable advantage of increased delicacy and accuracy. Calibrated to linear measurements, a single scale division is equivalent to 1/242 mm. vibration of the plate.

The different pitches are established by varying the capacity, and these resulting tones are measured by comparing them with Edelmann forks and Galton whistles. For higher tones, ranging from 4,000 to 13,650 vd., we use smaller inductance coils with higher frequencies, and the frequencies are computed from capacity and inductance. In the table of results those tones which were determined directly are indicated by *d*. Those which were computed are preceded by *c*. The method of computation for the higher tones is relatively simple, employing the known measurements of capacity and inductance in the formula $f=\frac{1}{2\pi\sqrt{LC}}$. We could determine L from the known capacity and pitch for several pitches; and we then used that with readings from the condenser to determine the other unknown pitches. Probably what we called L was partly C in parts of the circuit other than the condenser, but that would not affect our comparisons.

For a more adequate idea of the apparatus itself, the accompanying diagram may help.

A supplies filament with current to heat it, thus providing an electronic discharge from the filament to the plate.

B provides an independent voltage from the plate to the filament; controllable by lamps.

C Grid circuit through middle inductance.

D Oscillating circuit composed of variable condenser and upper inductance, producing by its oscillations differences of potential between the grid and the filament.

E Telephone circuit in which are produced oscillations by virtue of the variable coupling of the upper and lower inductances.

If we consider the filament to be hot, thus supplying free electrons, and the 220 volt supply to be sending a current through circuit *C* from the plate to the filament and through the lower inductance back through the lamps to the plate, there will be thus induced in the upper inductance a voltage which will create an alternating current in circuit *D*. This circuit

will have a frequency dependent upon the natural frequency of the circuit *D*, which may be evaluated as approximately $f = \frac{1}{2\pi\sqrt{LC}}$, in which *L* is the value in henrys of the upper inductance, and *C* is the capacity in farads present in the variable condenser. The frequency, *f*, is measured in cycles per sec.

The alternate charge and discharge of the condenser will cause changing differences of potential between the grid and the filament of the vacuum tube, and these changes produce in turn relatively large changes in the electronic flow in the plate current, *C*. These changes in the latter circuit again induce magnified voltages in the upper inductance. The cycle repeats itself, providing larger and larger currents in circuit *C*, until it effects a maximum of variation of the current in circuit *D*, where the "static" condition of an alternating current constant in its effective value has been reached.

This "steady" alternating current in circuit *D* induces a similar voltage in the lower inductance, which in turn sends it through circuit *E*. *E* thus has the same frequency as *D*.

The above summary represents the plan of apparatus necessary to produce a pure tone of constant pitch in the telephone receiver.[2] With the exception of the receiver itself, the apparatus is arranged on a rubber-covered table in *E*'s room. The receiver is isolated in the adjoining sound-proof room and is held constant in a standard. Further to insure the same position, the end containing the plate is inserted in a hole in the center of an upright lead sheet 14 by 14 in. This lead plate incidentally absorbs the sound waves which go back, and prevents reflection.

Method and Results

Briefly, the essential elements in the experiment are, first, to determine the amplitude of vibration of the telephone plate for some known current strength; secondly, to measure the current which produces a liminal intensity; and finally, to measure the energy in ergs which effects the liminal sensation in the ear for various pitches.

The physicist's definition makes of intensity that quantity of energy which passes in unit time through unit area of a surface placed at right angles to the direction of propagation of the sound. It depends primarily upon three factors: the amplitude and rate of vibration of the vibrating medium, the distance between the ear and the vibrating source, and the area of the vibrating source. The first two factors comprise the variables in the Wien-Rayleigh formula, which we use to establish the relation between strength of current and the intensity of the resulting tone.

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[2]The telephone used is one furnished by Kohl as part of Wien's instrument for measuring amplitude of vibration of the plate by means of a light wave reflected from a mirror on a lever. In the center of the plate is fastened a small steel rod to which we attached a glass rod for our linear calibrations.

$$A = \frac{C\,p_0}{2k} \cdot \Delta^2$$

$$\Delta = 0.147 \frac{k}{C^2} \cdot \frac{(2N)^2\ A\ R^2}{q}$$

A = energy per sec. passing through a square cm. of surface
C = rate of transmission of sound
p = own tone of the vibrating plate
k = index of specific heat
N = rate of tone (pitch)
R = radius of plate
Δ = relative pressure amplitude
q = distance between the ear and the plate

Before beginning the actual experiment, it was necessary to calibrate the different units of the apparatus to absolute terms. The amplitude of vibration for different current strengths was determined by attaching a very fine glass rod to the center of the plate with beeswax, and measuring its oscillations through a micrometer eye-piece. The current was read in terms of scale divisions on the string galvanometer with readings from an ordinary D'Arsonval and a rectifier of molybdenum used as a check for the lower tones.

Further calibration established the translation of the plate vibrations to galvanometer oscillations, and a consequent reduction of both to amplitude in mm. When these factors are known, it becomes relatively easy to determine the amplitude of vibration effected by the minimal intensities of various pitches; and, supplying this variable to the Wien formula, the total energy in ergs may be computed. A considerable amount of preliminary practice work was done with one standard tone of 120 vd., for which students from the elementary psychology classes acted as *O*s. While disparity in individual sensitivity was markedly apparent, an average of these measurements established the liminal energy for this tone in the region of 5.10^{-9} erg.

With the consequent addition of the tuning apparatus, more factors have become involved in the computation, but the method has remained essentially the same. The experiment lasts about one hour, with frequent rest intervals to prevent fatigue. The *O* is seated in the sound-proof room, the distance between the ear and the telephone plate being kept a selective constant by means of a head and mouth rest (sealing-wax biting board.) Reactions are transmitted to the apparatus room by means of a simple code of four responses made with a telegraph key and sounder, and representing the appearance, disappearance, decrease, and increase in the stimulus intensity. Verbal communication, though rarely necessary during the trials, is available by means of a rubber tube inserted through the wall.

The work of *E* involves the establishing of a desired pitch by combining certain units of capacity, and the adjusting of the inductance coils to provide a standard amplitude of current through the string galvanometer. The method of minimal changes has been used for the majority of the measurements, the limen being established, first, by subtracting units of resistance until the tone is heard; secondly, by adding them until it declines to inaudibility. In each step, some specific intensity is used as a constant to add to or to substract from. The determination of Weber's law follows the same general method.

With the high tones above 4,000, the amplitude of vibration becomes difficult to measure accurately, even in so delicate an instrument as the Edelmann galvanometer, and the readings are consequently recorded in

terms of unit resistance. For this purpose we have found the Leeds-Northrup rotating model to be of valuable assistance to ease and accuracy. In this series the current is left constant, and the telephone shunted around a resistance, the current through it being decreased by changing the resistance.

The bulk of the experiment was performed with 6 trained *O*s, all of whom were advanced students of psychology or assistants, including Miss Mary Palmer and Miss Sugi Mibai, graduate students, Mr. Richard Page, Mr. Adelbert Ford, Miss Edna Gordon, and Mr. Ernest Skaggs, assistants. Professor Pillsbury occasionally acted as observer, and was an indefatigable source of assistance in every phase and problem of the work.

The results of the work on these comparative limens are combined in Table B.

Prior to the addition of the tuning apparatus for different pitches, some preliminary work was done on Weber's law with a constant stimulus of 120 vd., the tone induced through the plate by a 60-cycle alternating current. The first method utilized a sliding rheostat for grading the intensity. Following the establishment of the individual limen, the tone intensity was increased or decreased by very slow manipulation of the rheostat; and whenever *O* reported an audible difference the current intensity was read in scale divisions on the string galvanometer and recorded. The averaged results from the 6 *O*s produce a general fraction of .2844, with a P.E. of .069.

In the second method, the telephone was placed in shunt with a Leeds-Northrup resistance box, and the tonal intensity was varied by passing the greater part of the current through the resistance. The readings in this series were recorded directly from the variations employed by *E*, and hence the table values read in ohms. Selecting first a minimal and than a maximal point, the limen was first established as in the preceding method. Resistance was then increased or decreased by steps of 1, 2 or 5, etc., the *O* reacting whenever he noticed a difference in the intensity of the tone in either direction. In this method, the shunt box was off the circuit, and the ear placed close to the telephone. The resulting fraction of .3152 is somewhat larger than that obtained by the first method, while its P.E. of .9422 is a trifle less.

In order to see whether different pitches would exhibit the same appreciable gradations of intensity, the establishing of certain limens was followed, where time permitted, by further experiments on Weber's law. The tones were selected from different portions of the scale, including particularly the areas surrounding the apparent turning points of intensity. In each instance, the limen as determined by previous experiment for a specific tone was used as the initial intensity or starting point.

TABLE B

Tone	Pr	Pg	M	Go	Fo	Sk	Wien
*d*120	5.10^{-9}	8.10^{-8}	2.10^{-7}	8.10^{-11}	1.10^{-9}	1.10^{-9}	
*d*341⅓	6.10^{-13}	3.10^{-11}	2.10^{-10}				
d 384	4.10^{-13}	9.10^{-12}	5.10^{-10}				
400							3.10^{-14}
d 426⅔	7.10^{-12}	6.10^{-11}					
c 512	5.10^{-13}	3.10^{-11}	3.10^{-10}				
d 576	3.10^{-12}	3.10^{-11}					
d 640	3.10^{-12}	2.10^{-11}	4.10^{-10}				
800							7.10^{-15}
c 960	3.10^{-12}	2.10^{-12}					
*d*1189	2.10^{-11}	9.10^{-11}	8.10^{-10}				
1600							1.10^{-15}
*d*1726⅔	1.10^{-13}	5.10^{-12}					
*c*2048	1.10^{-13}	4.10^{-12}	1.10^{-12}				
*c*2304	2.10^{-13}	4.10^{-12}	3.10^{-11}				
*c*2560	6.10^{-14}	6.10^{-14}					
*c*3072	2.10^{-14}	2.10^{-14}	5.10^{-12}				
*c*3200							5.10^{-16}
*c*3413¼	1.10^{-15}	5.10^{-14}	3.10^{-12}				
*c*3840	8.10^{-15}	3.10^{-13}	7.10^{-13}				
*c*4096	4.10^{-15}	7.10^{-14}	1.10^{-12}				
*c*5120	2.10^{-14}	6.10^{-13}	1.10^{-11}				
*c*6400	1.10^{-14}	8.10^{-14}	3.10^{-13}				3.10^{-15}
*c*8192	3.10^{-13}	5.10^{-13}	4.10^{-11}				
*c*9216	3.10^{-13}	6.10^{-13}					
*c*10240	6.10^{-13}	3.10^{-12}	9.10^{-11}				
*c*12288	9.10^{-11}	2.10^{-12}	3.10^{-11}				5.10^{-14}
*c*13650⅔	7.10^{-11}	8.10^{-9}					

With this as a basis, the *O* reported the first audible increase between this standard tone and a series of comparison tones of different intensity. This intensity then in turn became the starting point for a further increase, and so on up the scale. In the descending order, *E* gave the tone of maximal intensity as the starting stimulus, and *O* reported the first noticeable decrease in intensity, each subsequent determination becoming, in turn, a comparison basis for an ensuing weaker intensity.

A practical example may afford a clearer explanation of the specific measurements here. For instance, the liminal intensity for a tone of 512 vd. read, in terms of resistance, as 10 ohms. With this used as the initial intensity, *E* then decreased the resistance until *O* responded to a noticeable increase in the tone. Five such trials were made around this liminal value, and their average was accepted as the boundary of the first "step." The resistance was then set at this average, and this intensity was given as a standard or starting tone for the second step. The intensity was again increased until *O* designated his awareness of a change, the five repeated trials occurring here also as checks; and their average was accepted as the upper measure of the second step, or the lower standard intensity for determining the third increment. The procedure for the descending series of intensities was simply a reversal of direction, using this same method.

Table C includes the results on Weber's Law as hitherto determined. The fractional increment in this case represents an average for 14 ascending and 14 descending steps.

Translated into terms of intensity, the first step corresponds to a liminal sensation, while the maximal or fourteenth step provides a tone very easily audible throughout the room. The quantitative equivalents in ergs for these maximal points have not yet been computed, but it may be said in general that the fourteenth step is comparable in intensity to the average conversational tone of the speaking voice. Accepting this general hypothesis, and the apparent validity of Fechner's law, it seems safe to assume that the complete range of intensity gradations for the human ear would not exceed 100.

In these experiments, we have put into actual practice Fechner's suggestion for the measurement of sensations by using the just noticeable difference as the unit of comparison. Audition furnishes the ideal sense for these measurements because of the large fraction of Weber's law, and hence the small number of steps required. Our results indicate that there are but fourteen different steps, *i.e.*, fourteen different units, between the limen and a tone as loud as the ordinary speaking voice.

The acquisition of results from the louder regions of intensity has been somewhat curtailed by this method, owing to the 1000-ohm limit of the resistance box. It is highly desirable to extend the number of steps to as loud an intensity as can be practically obtained, and possibly this phase of the work will be carried on later in our laboratory. The results so far obtained, however, indicate that the principle of Weber's law does

TABLE C

	Palmer			Page			Mibai		
Rate	Limen	Fraction	P.E.	Limen	Fraction	P.E.	Limen	Fraction	P.E.
120	5.10^{-9}	.4152	.0422	8.10^{-8}	.3961	.031	2.10^{-7}	.433	.0106
384	4.10^{-13}	.2792	.0847	9.10^{-12}	.2982	.074	5.10^{-10}	.4012	.125
512	5.10^{-13}	.26	.0276	3.10^{-11}	.304	.0313	3.10^{-10}	.418	.083
960	3.10^{-12}	.3031	.008	2.10^{-12}	.2054	.73			
1706⅔	1.10^{-13}	.209	.0658	5.10^{-12}	.293	.1037			
2048	2.10^{-13}	.196	.0712	4.10^{-12}	.2902	.081	1.10^{-12}	.3011	.086
2560	6.10^{-14}	.143	.106	9.10^{-3}	.286	.008			
3413½	7.10^{-15}	.273	.0296	5.10^{-14}	.1832	.0915	3.10^{-12}	.215	.0416
3840	8.10^{-15}	.2021	.046	3.10^{-13}	.2650	.993	7.10^{-13}	.2974	.0642
4096	4.10^{-15}	.1779	.0531	7.10^{-14}	.201	.7261	1.10^{-12}	.268	.072
6400	1.10^{-14}	.1462	.114	8.10^{-14}	.205	.05	3.10^{-13}	.2739	.084
9216	3.10^{-13}	.304	.091	6.10^{-13}	.495	.137			
12288	9.10^{-11}	.528	.1731	2.10^{-12}	.5634	.1009	3.10^{-11}	.6743	.017
13650⅔	7.10^{-11}	.4794	.092	8.10^{-9}	.8374	.209			

hold rather consistently for sound within certain limits, although the fraction is in no two instances identical, probably because of the errors of observation. The fraction near the limen shows consistently the lower deviation from the Law. With certain pitches, particularly in the lower range, it approaches one-half; in the medium range, it seems to maintain itself roughly at one-third or slightly less; in the upper range of the tones we used, around 12288 vd., it again approaches one-half or more.

In contrast to the conclusions of Smith and Bartlett, our data establish a slightly higher limen, in many cases, for the descending order of intensities than for the ascending, and the number of steps, when variable, is usually larger. No great divergence from these general tendencies was apparent in the results from different *O*s, the real contrasts occurring in the differential limens themselves and in different sensitivity to different pitches (Table B).

TABLE D

Table D includes fourteen steps from the ascending series of intensities for Miss Palmer. It serves to illustrate the variations in the fractional increments near and above the limen for tones selected from representative parts of the pitch range.

Steps	120 vd.	512	1706	2048	3840	6400	9216	12288
1	.468	.4325	.501	.4572	.571	.4218	.4273	.732
2	.4021	.3063	.4532	.396	.4032	.436	.561	.741
3	.4936	.491	.28	.4008	.401	.2997	.4821	.7064
4	.476	.3056	.278	.35	.312	.436	.4732	.623
5	.3495	.234	.2043	.2432	.2934	.171	.324	.544
6	.427	.2578	.3161	.2791	.2016	.203	.3041	.6921
7	.4241	.146	.2009	.268	.197	.1742	.3721	.5177
8	.305	.2932	.1937	.1104	.24	.2621	.209	.532
9	.3942	.205	.216	.3	.1911	.1287	.2573	.409
10	.401	.2005	.1867	.1873	.206	.1009	.3021	.5083
11	.43	.1893	.26	.29	.2173	.162	.256	.48
12	.372	.256	.1999	.19	.187	.2907	.305	.5112
13	.3589	.227	.254	.283	.272	.29	.49	.573
14	.47	.2436	.2126	.251	.33	.1894	.3783	.5805

Principal among the introspections from various *O*s was the observation that a maximal degree of attention during each experiment is necessary for valid judgments. The entrance of a fatigue factor always correlated with higher and more variable limens, and with enlarged and more uncertain increments of change. Careful consideration was, therefore, given to the *O*'s introspection of general feeling.

Some *O*s frequently reported auditory after-images and a difficulty in distinguishing the true minimal stimulus from subjective effects. This phenomenon apparently increased, rather than decreased, with practice, the higher sounds producing a more striking effect than the lower ones. In addition it may be

stated that the three *O*s having the lowest limens, and correspondingly the greatest acuity, encountered this difficulty most frequently. Two check-experiments with minimal values in intensity for 512 and 8192 vd., which employed the method of right and wrong cases, produced for them respectively an average of 78 and 81 correct perceptions, while for the *O*s less affected by auditory after-effects the general average of correct responses was 89%. The specific method in these two experiments was simply that of giving the warning signal 50% of the time when no current was on, and 50 % of the time when it was effecting a minimal intensity of vibration on the plate, and recording the percentage of correct and incorrect responses.

Kinaesthetic imagery seemed in general to predominate over visual, its effects occurring in a carrying-over of strain sensations of attention, and a feeling of effort to classify the different tones in some way.

The first three or four experiments for each *O* showed rather marked practice effects, but these did not appear subsequently in spite of repeated checks. The training seemed really to consist of increased attention and familiarity with reaction signals, rather than to involve any fundamental improvement in acuity.

One *O* reported difficulty in responding when the sound-proof room was illuminated, but it is probable that darkness merely mitigated a possible visual distraction for him.

The three lowest limens were secured from musically-trained *O*s; the higher limen and the larger fraction belong to an Oriental student with no musical experience; but the real significance of these factors cannot be definitely ascertained without further experimentation.

Conclusions

That tones of different pitch correlate with different sensitivity in the human ear is indicated by the difference in energy required to elicit response to their liminal stimuli.

Tones of the upper middle range are more easily perceived than tones either above or below it. Our results place these turning points respectively in the regions of 1000 and 6400 vd. Within these regions are apparent inconsistencies which illustrate differences in sensitivity both for certain tones and for the individual ear which reacts to the stimuli.

For Wien, the point of greatest sensitivity lies in the region of 3200 vd. Our results approximate 3483⅓ for two *O*s, and 3840 vd. for the third *O*.

Weber's law as applied to audition apparently holds true with a fraction of about one-third throughout the middle range of intensities. The fraction is larger for low tones and for very

high tones. The fraction is also larger near the limen, decreasing universally in the third, fourth, or fifth step. Whether this result is consistent through the upper range of intensities it has not been possible to determine until our apparatus is modified to produce greater intensities.

Kinaesthetic and auditory imagery are evidently predominant over visual imagery for all *O*s in the experiment, and there appears to be some correlation between auditory imagery and the limen of tonal acuity.

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